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Acoustic Radiation Due to Wave-Breaking

A Paper Presented at the 123rd Meeting of the Acoustical Society of America at Salt Lake City, UT, 11-15 May 1992

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PREFACE

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13. ABSTRACT *(Maximum 200 words)*

While wave-breaking is continually occurring at the sea surface, it's transient and sporadic nature makes it difficult to measure. Experimental results are presented which show how acoustic methods can be used as a remote sensor of this fundamental process. Sea surface-generated acoustic radiation (40 to 4000 Hz) is directly related to a quantitative measure of the boundary dynamics; i.e., the Toba variable. The frequency spectrum of the radiation remains remarkably unchanged over a wide range of environmental conditions but the correlation between the sound pressure level and the Toba variable undergoes an abrupt change when spilling breakers start to occur. Results support the use of acoustics to remotely measure the rate of energy being dissipated by wave-breaking and the characteristic length of the wave-break. Theoretical studies have related the field measurements to analytical and laboratory results cited in the literature indicating that remote monitoring of the rate of occurrence and size distribution of "infant" (freshly entrained) bubbles may be possible if splashes on the surface do not radiate significant sound. (Work sponsored by ONR and NUWC.)

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This document is a transcript of the invited presentation given by Dr. Kennedy on 11-15 May 1992, at the 123rd Meeting of the Acoustical Society of America at Salt Lake City, UT.

SLIDE 1: Presentation Outline

The topic of the presentation is the sound generated by a breaking wave. Specifically the presentation discusses the question of whether or not one can practically use measurements of sea-surface-generated acoustic radiation to remotely monitor various parameters of the surface wave field. Two aspects, or measurement types, will be covered. First, it will be argued that a *direct measurement* of the surface dipole source spectrum results in a function described by only two parameters. These parameters are measures of the *Wave Dissipation Due to Wave-Breaking* and the *Characteristic Length of Whitecaps*. Second, parameters of the bubbles generated by the wave-breaking process may be inferred using parameter identification algorithms based on a theoretical model of the sound field. Parameters discussed are: *Bubble Generation Rate* and *Bubble Number and Size Distributions*.

ACOUSTIC RADIATION DUE TO WAVE-BREAKING

By: R.M. Kennedy, S.A.L. Glegg, and P. Elisseeff

Presentation Outline

Can Sea-Surface-Generated Acoustic Radiation be Used to Remotely Measure Sea-Surface Wave Parameters?

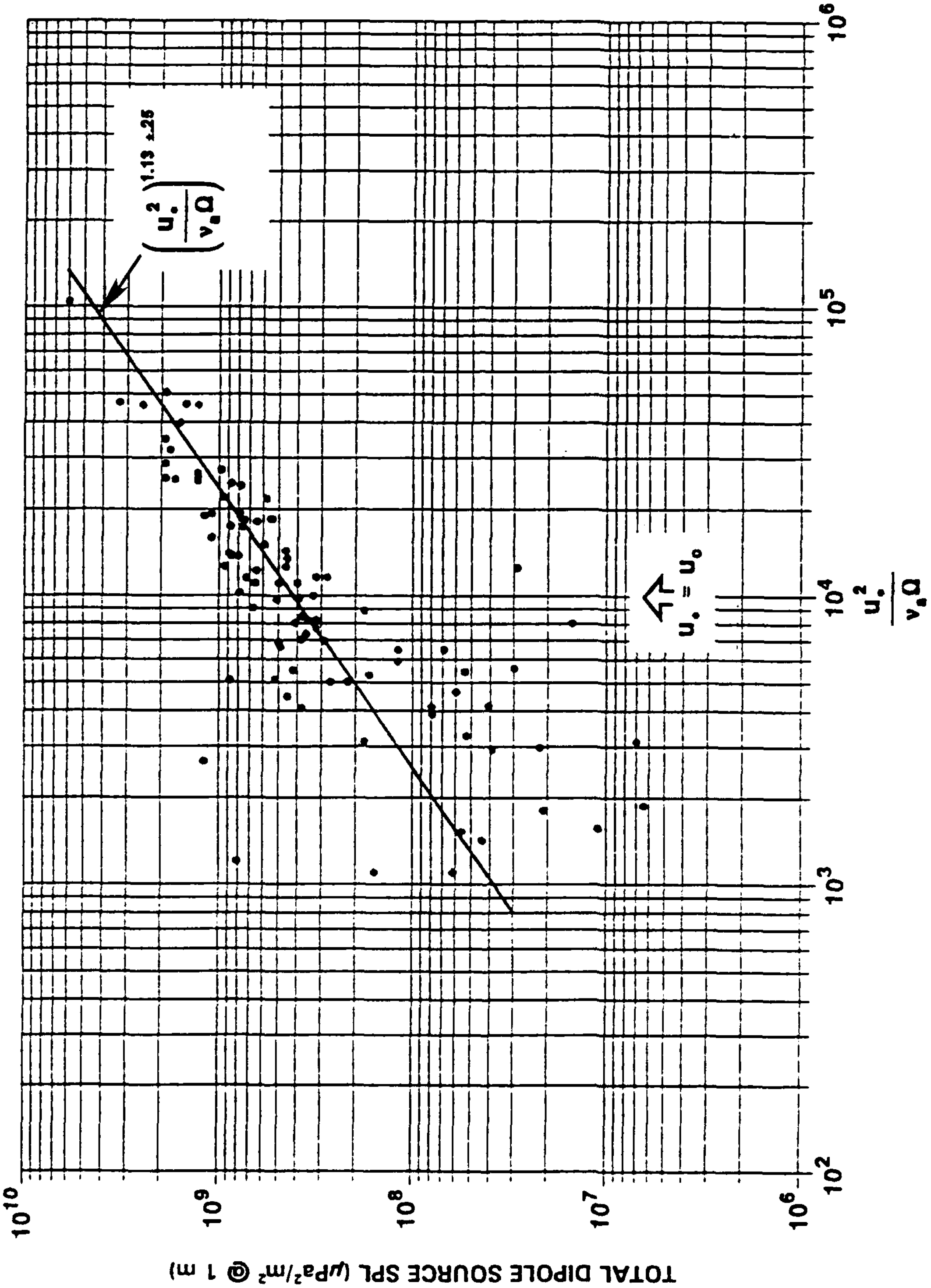
- Direct Measurement
  - Wave Dissipation Due to Wave-Breaking
  - Characteristic Length of Whitecaps
- Inferential Measurement
  - Bubble Generation Rate
  - Bubble Size Distribution

SLIDE 2: Dipole SPL Relationship to Sea-Surface Conditions

Let us begin by reviewing some pertinent acoustic measurements which relate surface dipole sound pressure levels (SPL) to air-sea boundary processes and surface gravity wave variables. This data has been presented elsewhere[1] and time permits only a summary description here. The data was obtained from a relatively deep water basin in the Bahamas, which was totally isolated from shipping and industrial acoustic sources. A parametric spectral estimation scheme was used to isolate the source spectrum of near-surface dipole sources from a measured vertical cross-spectral density function.

This figure presents, along the ordinate, the frequency-integrated total dipole source sound pressure level as an ocean surface density function. The frequency range of the measurements is 40 to 4000 Hz. The units are μPa^2 (referenced to one meter) per m^2 of ocean surface. The independent variable, along the abscissa, is a nondimensional variable derived by Yoshita Toba[2] to characterize air-sea boundary processes. This variable has been widely used to describe the overall conditions of the air-sea boundary relative to percentage whitecapping coverage, sea roughness lengths, and certain aerosol salt concentration variables. The Toba variable has been chosen here, vice wind speed, for two reasons. First, these measurements were made under fetch-limited conditions and thus wind speed is an incomplete description of the sea surface, and second, it emphasizes the fact that wind is a secondary variable in the process; i.e., the dipole source mechanism is presumably the result of the formation of bubbles and spray by wave-breaking. The air-sea parameters involved in the Toba variable are: the wind friction velocity (u_*) which was calculated from measured wind speed assuming a logarithmic wind profile under neutrally stable conditions[3], the kinematic viscosity of air (ν_a), and the frequency of the dominant component of the surface gravity wave field. The latter variable was not measured directly but calculated based on measured wind speed and direction, basin geometry, and a JONSWAP model. There are two characteristics to be noted in this figure. First, the dipole sound production is seen to be directly proportional, within measurement error, to the Toba variable. Second, the variability of the experimental points partitions the data into two distinct regions separated by the point at which the friction velocity is equal to the minimum phase speed of the wind-wave field (u_c).

DIPOLE SPL RELATIONSHIP TO SEA-SURFACE CONDITIONS



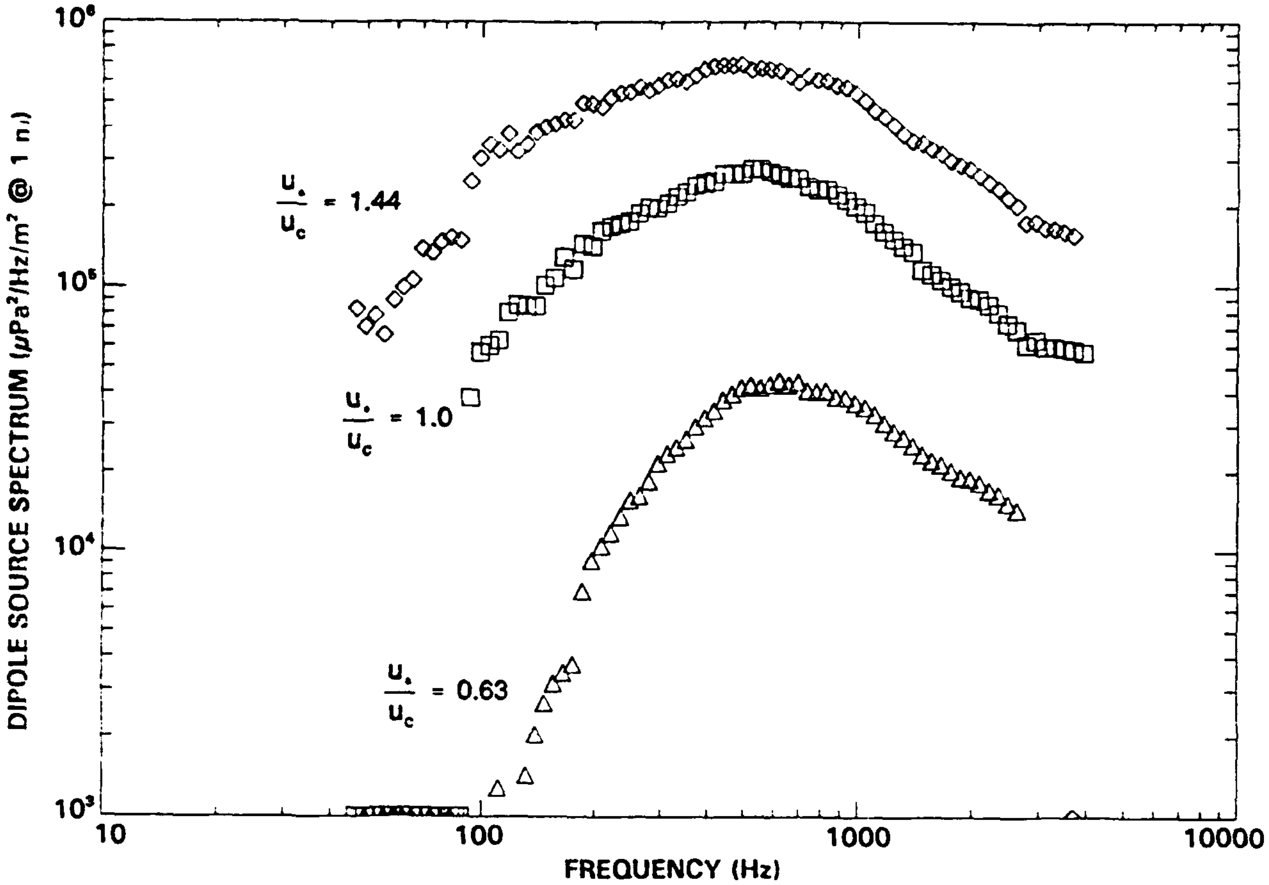
Brian Kerman[4] has shown that this marks the point where the turbulence at a free surface is sufficiently energetic to exceed the energy associated with the surface tension. Numerous articles have shown that this is also the point at which the sea surface transitions from aerodynamically smooth to rough. In the context of the present discussion the important point to be made is that the Toba variable below a value of 10^4 is no longer as good a predictor of the acoustic source level, and that this is likely a result of the importance of surface tension which is not included in the Toba variable. However, despite this obvious change in the total source level dependence on the air-sea boundary process, slide 3 shows that the acoustic spectral character is unchanged by this epoch; i.e., there is no indication that the acoustic source mechanism changes. While the process by which the sea surface causes waves to break changes, there is no modification in the fact that wave-breaking entraps air bubbles and that the bubbles generate sound. Thus, monitoring the sound generated is a likely way to monitor wave-breaking, whatever causes it to break.

SLIDE 3: Surface-Generated Dipole Spectrum

This figure illustrates the general bandpass character of the dipole source frequency spectrum. The abscissa is frequency and the ordinate is spectrum level. These are three examples of the 101 spectra analyzed. The wind speed is parametized by a nondimensional friction velocity which is unity for incipient spilling breakers. Thus, the three curves span the sea conditions from smooth to rough.

Examination of the details of the spectrum shows that the frequency of peak energy and the lower half-power frequency are inversely proportional to the friction velocity but the upper half-power frequency (1600 Hz) is independent of sea conditions. Numerically the bandwidth is approximately 1400 Hz, which is not significantly affected by sea conditions. *A fundamental point is that practically, the acoustic source spectrum is defined by only two quantities. They can be usefully chosen to be the magnitude and the frequency of the spectral peak.* Thus, the data supports the conclusion that the actual sound mechanism, presumably air entrainment by breaking waves, is unchanged by the sea-surface condition. Changes in the surface wave field manifest themselves in changes in the magnitude and frequency of the acoustic spectrum only.

SURFACE-GENERATED DIPOLE SPECTRUM

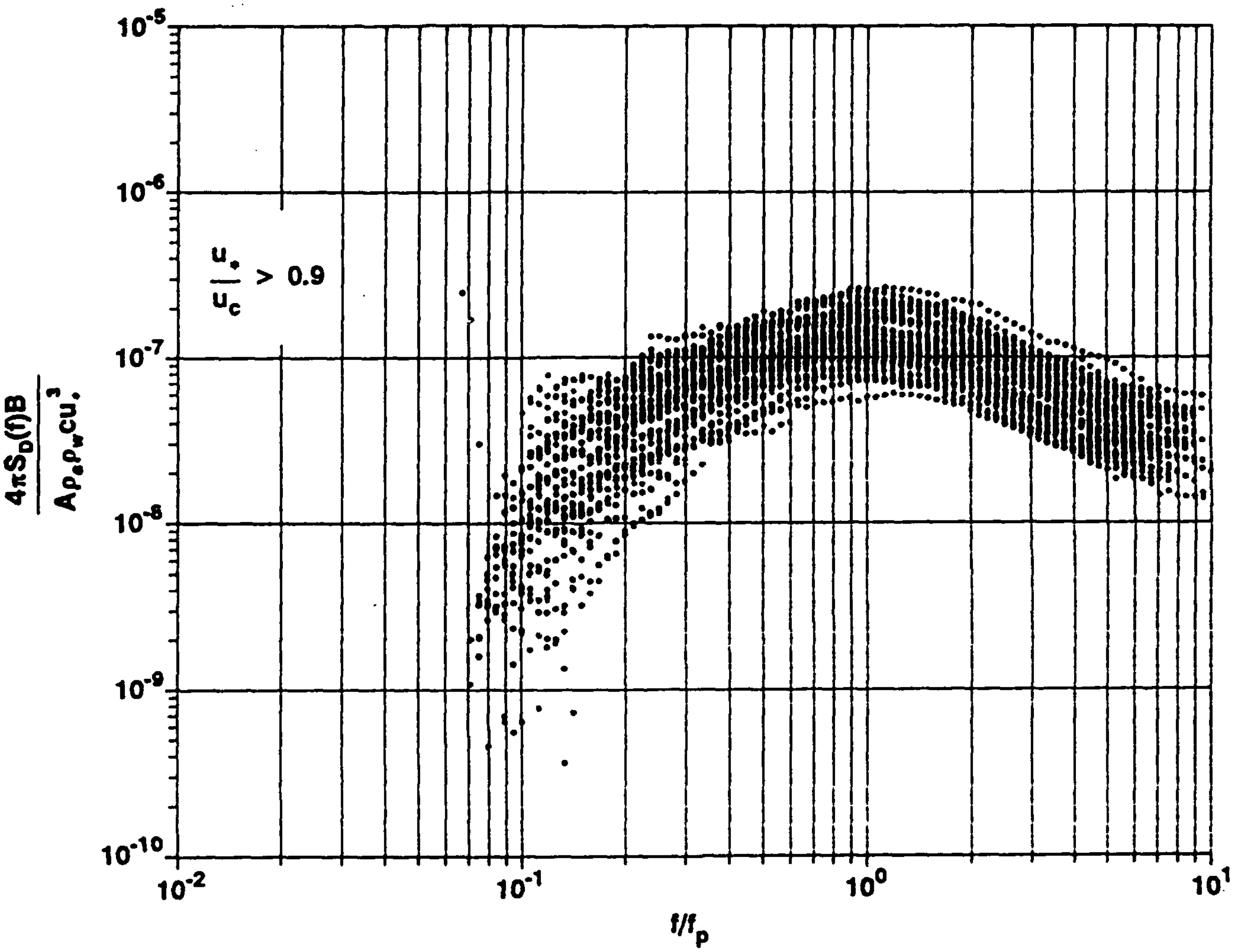


SLIDE 4: Equilibrium Range Gravity-Wave Scaling

Loewen and Melville[5] showed in laboratory tests that the acoustic energy generated by a breaking wave was proportional to the wave energy dissipated by the breaking event. Experimentally they found that the fraction of the energy dissipated by the breaking wave that radiated acoustically was 10^{-8}. It is desirable to see if that same result applies to the current field data. Since the wave dissipation in the field is a quite difficult quantity to measure, it is necessary to use a theoretical prediction of the rate of energy input into the surface-layer turbulence by wave-breaking in the gravity-wave equilibrium range derived by Owen Phillips[6]. The expression is based on observations of whitecaps that show that the process takes place over a wide range of spatial scales. Wave-breaking, which is quite local in a spatial domain, is necessarily quite broad in a wavenumber space. Phillips concluded that the spatial scales over which wave-breaking was dissipating the wind-generated gravity-wave field extended well beyond the dominant wavenumber into the equilibrium range. We use his result in this figure.

The ordinate of the figure is the dipole acoustic power per unit surface area nondimensioned by the Phillips expression for the rate of energy dissipated per unit surface area by wave-breaking in the gravity-wave equilibrium range. The abscissa is the acoustic frequency nondimensioned by the frequency of peak acoustic energy as did Kerman, 1984[5]. Note that only trials in which spilling whitecaps were present are included; i.e., $u_*/u_c > 0.9$. If data taken with an aerodynamically smooth surface is included, then the variability is significantly increased as discussed previously. However, the spectral form is unchanged. The figure demonstrates a coalescing of the spectrum within a factor of four. This field-measured data appears to be consistent with the Loewen and Melville laboratory result; i.e., the rate of acoustic energy produced by wave-breaking is proportional to the rate of wave energy dissipated by wavebreaking.

EQUILIBRIUM RANGE GRAVITY-WAVE SCALING



SLIDE 5: Transduction Factor and Surface Wave Variables

It is useful to derive a transduction factor defined as the ratio of the acoustic power generated per unit surface area divided by the rate of energy input to surface turbulence by wave energy. It is quantitatively equal to Loewen and Melville's "fraction of the dissipated wave energy radiated as sound". The expression is in terms of the measured dipole source area density function ($S_D(\omega_p)$), a geometric factor to account for the dipole radiation pattern, an acoustic bandwidth (B = 1400 Hz), and the proportionality factor in the Phillips expression (A). The value for the Phillips constant is not confidently known, however, use of a median value for A leads to a numerical value for the transduction factor (0.6×10^{-8}) which indicates that the field measurements are certainly of the same order of magnitude as the laboratory measurements.

The properties of this energy ratio are fundamental to the viability of the technique being proposed. Clearly, the ratio is stochastic and the value of the variance, or more usefully the coefficient of variation, of this random variable will determine the utility of the technique. Presumably the statistics of this quantity could be determined from a laboratory experiment of the type conducted by Loewen and Melville.

With an independent measure of u_*, an acoustic measurement yields an estimate of the Phillips constant (A). This variable opens a window into fundamental surface wave parameters. It is useful to comment on the relationship of this constant to typical parameters of the gravity-wave field. As shown in this figure, the acoustically-determined quantity (A) requires knowledge of several gravity-wave parameters. They are:

- p is a measure of the angular spread of the wave directional spectrum.
- β is the proportionality factor for the wavenumber spectrum and is related to the better known Toba constant which is the proportionality factor for the frequency spectrum.

- **Transduction Factor**

$$T_F = \frac{\frac{2}{3}\pi B S_D(\omega_p)}{A \rho_a \rho_w c u_*^3} \approx 0.6 \times 10^{-8} \quad \left(\begin{array}{c} T_F \approx 10^{-8} \\ \text{Loewen \& Melville, 1991} \end{array} \right)$$

$$= \left[\begin{array}{c} \text{Fraction of Dissipated Wave Energy} \\ \text{Radiated as Sound} \end{array} \right]$$

- **Surface Wave Variables**

$$A = 2(\gamma\beta^2)\beta I(3p)\, \ell n \left(\frac{r}{C_D} \right)$$

$$I(p) = \int_{-\pi/2}^{\pi/2} (\cos\theta)^P d\theta$$

$$\beta = \frac{\alpha}{4I(p)} = \left[\begin{array}{c} \text{Proportionality Factor for} \\ \text{Surface-Wave Wavenumber Spectrum} \end{array} \right]$$

α = Toba Constant

$$\gamma\beta^2 = \left[\begin{array}{c} \text{Related to Ratio of Energy Dissipated} \\ \text{by Wave-Breaking to Energy Input Wind} \end{array} \right]$$

C_D = Surface Drag Coefficient

$\gamma\beta^2$ is related to the ratio of energy dissipated by wave-breaking to that input from the wind.

r is a free parameter that accounts for the uncertainty in equilibrium range (0.3 to 0.5).

The point here is that the basic quantity measured acoustically can be used in conjunction with other measurements to estimate some quite fundamental surface dynamic parameters.

SLIDE 6: Measuring the Whitecap Characteristic Length

As stated previously, the frequency of peak energy changes monotonically with any measure of the sea surface. Let us assume for the moment that the sound is caused by the oscillation of bubbles entrained in the breaking wave and that the frequency of peak energy scales with the size of either the entrained bubble or bubble plume. We might thus expect to see the frequency of peak energy scale with some measure of the size of the breaking wave.

Historically a whitecap characteristic length scale has been defined as the square root of the product of the length of the whitecap along the wave crest and it's length transverse to it. A summary has recently been published by Wu, 1992[7] of measurements of this parameter. The Bortkowski measurements are from a fully developed sea and the Snyder measurements are from a fetch-limited sea. For the fully developed sea we can assume that the velocity of the dominant gravity-wave component is proportional to the wind speed and then utilize a deep water dispersion relation to express s in terms of the wavelength of the dominant gravity-wave component. The two measurements can be seen to reduce to a common form.

For the present measurement we can relate the measured frequency of peak energy to the wavelength of dominant gravity-wave component during the measurement and thus the whitecap characteristic length scale. The lower figure shows the measured frequency of peak energy on the ordinate and the inferred whitecap characteristic length scale on the abscissa. The regression line fit to the data shows, within measurement error, that the frequency of peak energy of the measured dipole source spectrum is inversely proportional to the whitecap characteristic length scale. We note that this development relied on the assumption that entrained bubbles are the principal acoustic process.

MEASURING WHITECAP CHARACTERISTIC LENGTH

- **Whitecap Characteristic Length(s)**

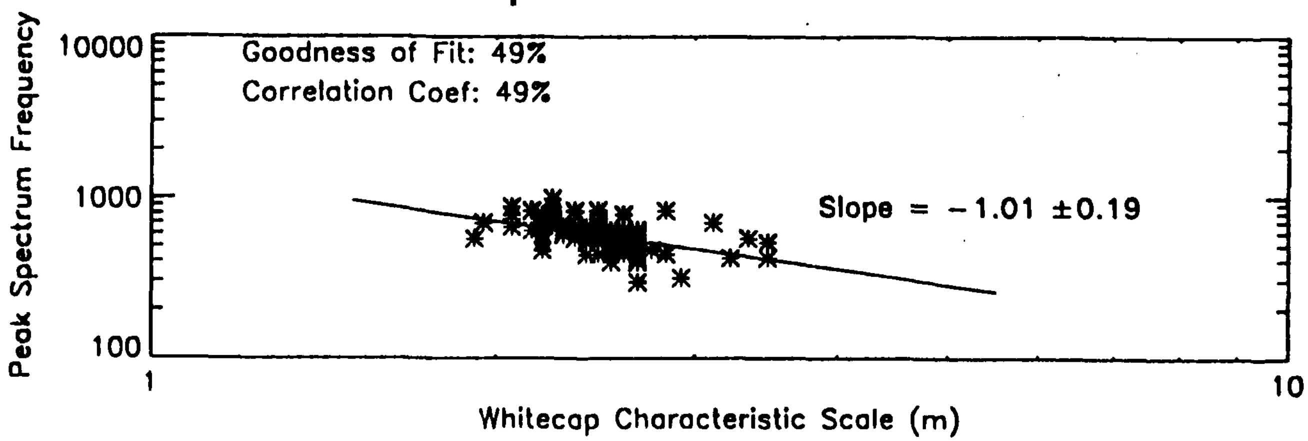
$$s = \alpha\, U_{10}^{3/4} \qquad \text{(Bortkowski, 1987)}$$

$$\frac{s}{\lambda} = 0.4\, \lambda^{-0.6} \qquad \text{(Snyder, 1983)}$$

$$\boxed{s = \beta \lambda^{3/8}}$$

- **Peak Energy Frequency (f_p)**

$$f_p = 1668\, \lambda^{-3/8}$$



SLIDE 7: Bubble Parameters Related to Acoustic Cross-Spectrum

We now proceed to a discussion of ocean parameters that can not be directly measured but rather quantities that can be inferred from models of the acoustic production process. A description of the model follows. Note that a model form for both entrained bubbles and spray striking the surface were developed, however, only the bubble oscillation form will be addressed here. The components of the model consist of a stochastic process which is stationary in time and homogeneous on the horizontal spatial variables. The random process can have an arbitrary vertical probability distribution. Each event in the process consists of the transient oscillation of a bubble or a collection of bubbles beneath a smooth pressure release surface. An arbitrary propagation model handles the transmission between the transient sources and the receiver locations. Because the summation is over a random number of events the statistical analysis utilizes the Carson's Theorem. The character of the damped oscillation has been documented by Professor Prosperetti[8] and a slightly modified form of his was used. There are three bubble parameters used. They are: (1) the number of collectively oscillating bubbles, (2) a bubble radius probability density function formed from a functional fit to the data of Medwin and Daniel[9] (with particular attention paid to fitting the large radius tail) with a maximum radius parameter, and (3) the rate of bubble generation per unit water surface area. Dual spatial observation points (for cross-spectral density purposes) are chosen in the water volume.

The cross-spectral density model form consists of four parts: (1) the rate of bubble generation, (2) a scaling to account for the reflection from the pressure release surface, (3) a propagation term, and (4) a bubble oscillation spectrum which involves damping, resonant oscillation terms based on the number of collectively oscillating bubbles, and the probability distribution of the bubble radius of acoustically active bubbles.

BUBBLE PARAMETERS IN AN ACOUSTIC CROSS-SPECTRUM MODEL

- Model Components
  - Transient Bubble Analysis
    - + Uniform in Time and On Sea Surface
    - + Arbitrary Distribution in Depth
    - + Carson's Theorem
    - + Arbitrary Propagation
  - Bubble Parameter
    - + Number Collectively Oscillating (N_1)
    - + Maximum Bubble Radius (d_1)
    - + Rate of Bubble Generation Per Unit Surface Area (γ)
- Model Form

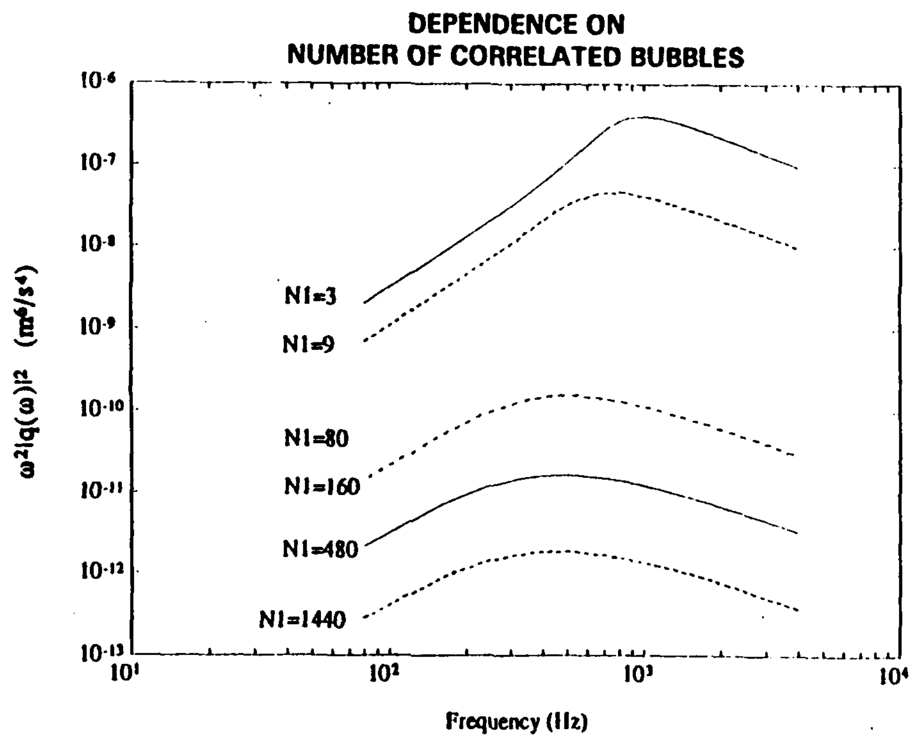
$$C_{pp}(\tilde{x}, \tilde{z}, \omega) = \frac{\gamma}{2}(kz_0\rho)^2 E\left[|q_n(\omega)|^2\right] P(\tilde{x}, \tilde{z}, \omega)$$

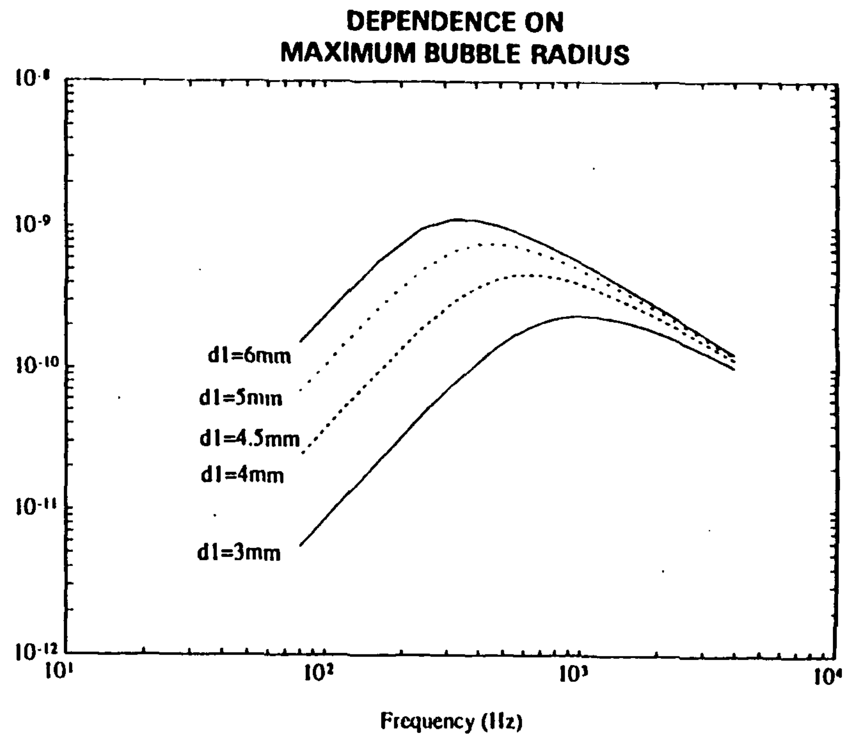
$$E\left[|q_n(\omega)|^2\right] = \sum_j n_0(R_j) \frac{4R_j^6 X_0^2 \omega_0^6 \Delta R}{(\omega_0^2 + b^2 - \omega^2) + 4\omega^2 b^2}$$

SLIDE 8: Model Parameter Dependence

For the model to be useful, the bubble parameters need to model the measured acoustic variable in a significant and, hopefully, a mutually orthogonal way. This figure illustrates model predictions of bubble source auto-spectral density for a range of two of the three bubble parameters. The abscissa is a log frequency scale from 10 to 10,000 Hz and the ordinate is the source spectrum on a logarithmic scale. The left-hand figure shows the dependence on the number of correlated bubbles oscillating and the right-hand figure shows the dependence on the radius of the largest individual bubble entrained. We see qualitatively that the model form matches the measured source spectrum in the sense that they are both band-limited functions with a peak energy in the hundred's of Hz range. This form is sensitively dependent on the analytical form fit to the Medwin and Daniel's measurements[10]. It is necessary to choose a form which carefully matches the large radius tail of the data. The range of maximum bubble radius is consistent with the 7.4-millimeter bubbles observed in the laboratory by Medwin and Daniel and field observations of Lamarre and Melville[11] where 5-millimeter bubbles were consistently seen.

BUBBLE SOURCE SPECTRUM MODEL PARAMETER DEPENDENCE

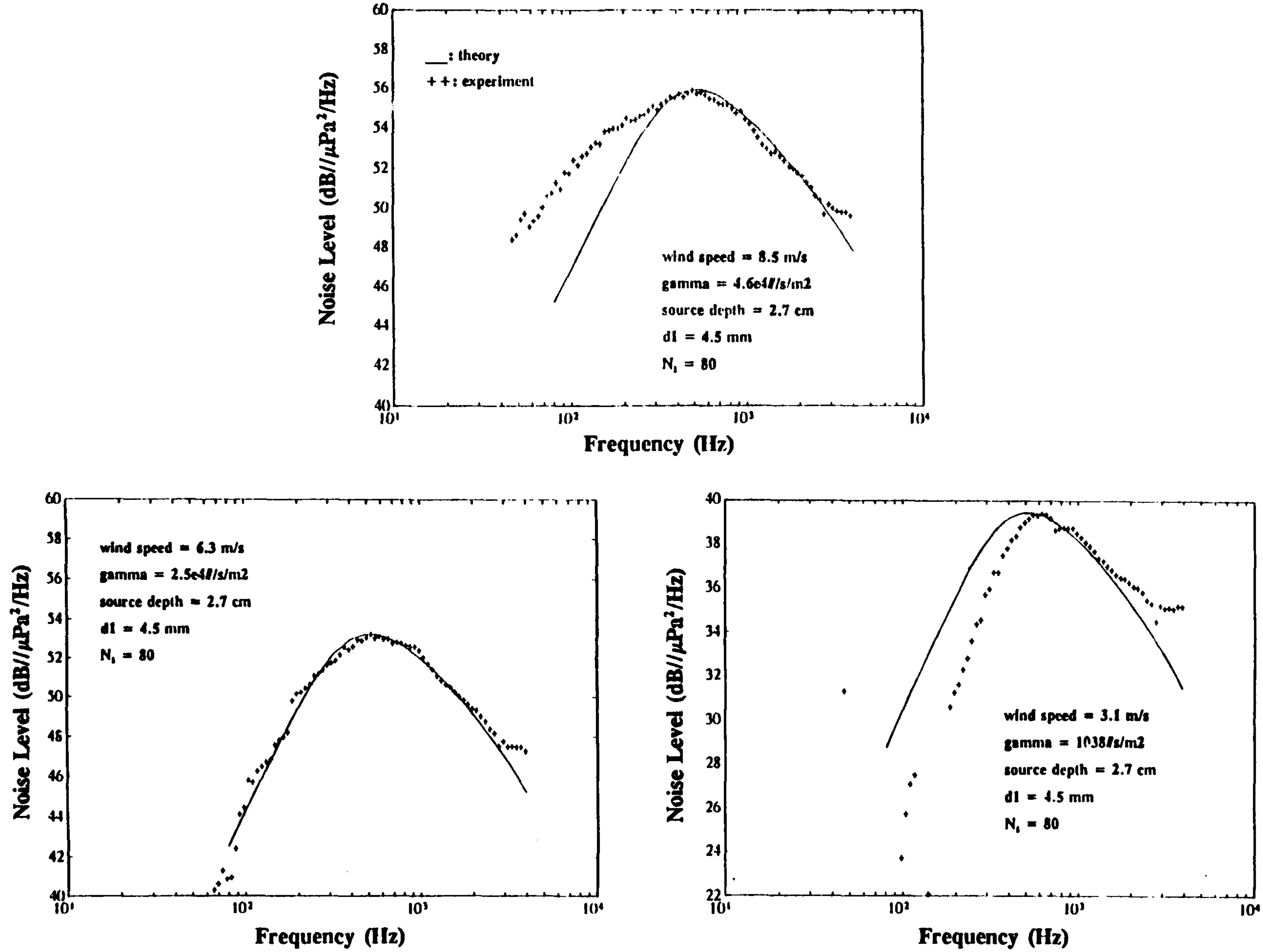




SLIDE 9: Model Data Comparison

This figure illustrates predictions of the acoustic auto-spectral density in a geographical configuration which matches the Bahama basin experiment described. The independent variable in all three panels is log frequency and the ordinates are the acoustic auto-spectrum at the hydrophone locations. This calculation was chosen because it allows a direct comparison of predicted and measured quantities. A single choice of the three bubble parameters was determined to best fit the 6.3 m/s wind speed case shown in the lower left-hand panel. It is seen that a quite good fit between the model and the experiment is possible if all three of the parameters are free to vary. In the other two panels, showing an example of a smooth and rough sea surface, the values of d_1 and N_1 are held constant but gamma is varied to give the fits shown. The fit is no longer very good. Not surprisingly the number of correlated bubbles and maximum bubble radius will have to be varied with the sea conditions to maintain reasonable quality fits to the data. There are over 100 entries in the measured data base and no attempt has been made, as yet, to determine if all three parameters can be found to vary in a consistent and physically meaningful way with the sea conditions.

DIPOLE SPECTRUM MODEL DATA COMPARISON



SLIDE 13: Summary

This figure summarizes the conclusions of the presentation relative to the two types of measurements described. The direct measurement of the surface dipole source spectrum results in a spectral form having a nearly universal form described by two parameters; i.e., the frequency and magnitude of the spectrum at it's maximum. These two parameters appear to be measures of the wave energy being dissipated by wave-breaking and a characteristic length scale of the wave-breaking process. The fraction of the wave energy dissipated that radiates acoustically is found to be within an order of magnitude of the value measured in the laboratory. In order to measure certain bubble production parameters that result from the wave-breaking events it was necessary to derive a theoretical expression which models the acoustic production process. Such a model form, for the pressure cross-spectral density, has been derived. The model contains three bubble generation parameters which, when independently varied, have shown a quite good fit to measured hydrophone autospectral density. The parameters appear to be a function of the sea-surface condition.

CONCLUSIONS

- Direct Measurements
  - Surface-generated source spectrum is nearly universal with only the magnitude and frequency of the peak energy changing with sea-surface conditions.
  - These parameters are measures of the wave energy dissipated by wave-breaking and the characteristic length of the breaking wave.
- Inferential Measurements
  - A model form with good agreement with data has been developed.
  - The model identifies bubble generation rate and the size and number of bubbles collectively oscillating.

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